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POST-FIRE DAMAGE ASSESSMENT OF A COMPOSITE WINGBOX

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NOTICES

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ABSTRACT

An evaluation of Composite Wing Boxes has been conducted to demonstrate the severity of composite fires and evaluate damage assessment techniques for large-scale composites. The fire test objective was to simulate the fire that would occur following a fuel spill from a large composite aircraft. The test fires simulate the fire that might occur following a pool fire under a static airplane for two scenarios: the first simulates an immediate response to a pool fire by a person located near the aircraft and the second fire simulates a response, five minutes after fire ignition. After the burn, samples from both scenarios were evaluated for changes in rheological and mechanical properties. Properties measured include weight loss, Tg change, thermomechanical properties (storage and loss modulus) and short beam shear strengths. Results from these tests will be presented and discussed. A fire damage description and damage evaluation methodology is outlined that is applicable to a variety of composite materials.

KEY WORDS: Composite, Fire Performance, Aircraft, Wing Box, Damage Assessment

1. INTRODUCTION

Composite materials are being used in increasing amounts in a variety of applications based on their stiffness, strength, reduced weight, and corrosion-free capabilities. They are typically fabricated by impregnating a fiber-based reinforcement with an organic polymer (resin) using a variety of manufacturing processes. The attractiveness of these materials lies in the ability to engineer them to provide a range of properties over conventional monolithic materials. They are currently used in a wide variety of industries, covering aerospace, marine, military, automotive, infrastructure, medical, sporting goods and others.

Typically, structural composites for the marine and infrastructure industries are based on glass reinforced polyester, vinyl ester or epoxy resins. Civilian and military aerospace applications generally use graphite or carbon reinforcement with a variety of resin systems depending on the application requirements. Some examples include empennages in the F-15, F-16 and F-22, secondary wing structures of the B1-B, portions of the fuselage of the F-22 and B-2, wing components of the F-22 and various engine components in all the aircraft. Resins used range from thermosetting epoxies to high temperature polyimides and some thermoplastics. Space applications use graphite-based composites with resins ranging from epoxies to cyanate esters. In infrastructure applications, fiber reinforced composites are attractive materials due to their strength and stiffness, as well as relatively lightweight which simplifies handling and installation. They are being considered for various uses, such as earthquake resistant structures, overpass reinforcement and repair and bridge constructions.

Composite materials also pose fire safety concerns due to the combustible nature of the organic polymer matrix. The inherent chemical nature and complexity of polymer matrix composites do not lend themselves to easy analysis of their behavior when exposed to fires. Heat transfer is anisotropic in composite materials and they selectively burn, produce smoke, release heat, chemically degrade, char and delaminate. Assessment of the fire hazard of composite materials has evolved over the past three decades to include measurement of flammability characteristics such as ignitability, flame spread, combustibility, rate of heat release, and smoke and gaseous byproducts during exposure to fire [1-20]. Due to the inherent complexity of composite materials, flammability is not readily quantified for complex, commercial systems and is a continuous on-going process. The continued development of new fibers and resin systems requires a continuous assessment and understanding of their fire performance.

This paper describes initial studies in understanding fire-induced damage and degradation mechanisms of composite materials typically used in military aircraft. Two composite wing boxes, fabricated from AS4/3501-6 graphite/epoxy, were tested under realistic pool fire scenarios, for two different response times (1 minute and 5 minute) for extinguishing fires. Temperature profiles on the wing boxes were measured using thermocouples to provide typical thermal histories for the tested cases. Samples were cut out of the wing boxes for further analysis, starting with visual assessment followed by thermo-mechanical studies. Test procedures and results are described below.

2. COMPOSITE WINGBOX BURN TEST

Efforts to create a lighter, faster, more efficient fighter aircraft has led to the increased use of composite materials. Composites are 24% of the airframe for the next generation fighter, the F-22. The limited fire data available on composites only addresses non-coated materials tested under ideal conditions (such as cone-calorimeter) [2,3]. With current standards, Crash/Fire vehicles may not arrive in time to prevent ignition these materials [4,17,20]. Composites continue to burn after the liquid fuel fire is extinguished. The continuing fire produces as much heat as pinewood when burning. Final extinguishment will probably require breaking apart obscuring structures and fully saturating smoldering areas with wet extinguishing agents. Fire department response to a fire on or near an aircraft must be in seconds to prevent irreversible damage. A continuous assessment of the composite components is required, due to

developments in materials, to determine damage levels and appropriate measures to ensure aircraft performance and safety.

The Air Force Research Laboratory (AFRL) has identified a need for this test series to provide fully controlled large-scale burn tests of graphite/epoxy composite materials based on the increasing use of composite materials [17-20]. The test fires simulate the fire that might occur following a pool fire under a static airplane for two scenarios. The first will simulate an immediate response (1 minute) to a pool fire by a person located near the plane with a 150 pound halon extinguisher. The second fire will simulate a lack of immediate response (5 minutes). The response will utilize hand line from a P-19 containing 3% AFFF solution. This test effort will consist of two (2) fires using two composite box wing structures, as test specimens.

All testing was accomplished at Test Range II, Tyndall Air Force Base, FL in facilities under control of the Air Force Research Laboratory (AFRL/MLQD). The hanger was instrumented to record the range of normal fire test. This data includes: temperature, combustion gases, and video in both the visible and infrared spectral regions. Six (6) samples were cut from each wing box top and bottom surfaces (24 samples in all) and provided for post-fire damage assessment.

3. DAMAGE ASSESSMENT METHODOLOGY

One of the goals of this effort was to establish a standardized methodology for the assessment of fire damage on composite structures in realistic fire scenarios. In such cases, no thermal history is typically available, which complicates the task considerably. It becomes necessary to thus understand the relationships between measured properties during post-fire assessment, degradation mechanisms and kinetics and thermal histories during controlled tests, such that material response in a realistic case can be established.

As such, the following methodology was established initially to assess the samples provided from the wing boxes:

1. Specimen Inspection
    a. Visual, Optical and Electron microscopy will be performed on all sample sets to evaluate extent of damage at all scales (macro- to micro-). Visual examination will be in the form of high-resolution digital photographs for macro-scale damage, optical and electron microscopy to show micro-scale damage.
    b. Parameters observed will include resin content, fiber diameter change, damage scale and size etc. Graded degradation will be evaluated in the thick samples also.
2. Degradation Analysis
    a. Standard analysis tools will be used to evaluate state of degradation of the samples. This will include TGA, DSC and DMA.
    b. Parameters evaluated will be Resin content or Weight loss as a function of time and Moisture content.
    c. For the thick samples, parameters will also be measured for changes in the thickness direction. This will be especially interesting for the 1 minute burn thick samples, where significant changes may occur on the surface, but not on the bottom side of the sample.
3. Thermo-Mechanical Properties

a. Properties of interest are Density, Interlaminar Shear Strength and Flexural Strength and Stiffness.
b. Density will also be measured as a gradient in the thickness direction for thick samples. Similar attempts will be made for Flexure and Interlaminar Shear properties, however there is no guarantee specimens will survive preparation procedures.
c. Due to the nature of the provided samples, any issues with sample preparation will be documented. Care will be taken to ensure minimal damage during preparation, however any internal damage may cause specimens to fail prematurely and will be noted as such.

There are other assessment techniques, including Non-Destructive Evaluation (NDE) that can also be used, but are not included within the scope of this initial assessment.

3.1 VISUAL DAMAGE ASSESSMENT

All the received samples were examined and photographed for visual damage. A visual damage index was created to assess and compare each sample, and is documented in Table 1. Damage in the samples ranged from minimal surface damage to significant weight loss, matrix degradation and fiber/matrix separation.

Table 1: Visual Damage Index for Samples from Composite Wing Boxes

Visual Damage Index and Degree (1 – Slight to 3 – Severe)	**Sample Condition**
A –1, 2, 3	Little Surface Damage, Slight Discoloration
B – 1, 2, 3	Heavy Discoloration – Scorching
C – 1, 2, 3	Pitting/Gouges or Gashes
D – 1, 2, 3	Fiber/Matrix Separation, Matrix Decomposition
LS	Layer Separation

Table 2 documents the samples, exposure times and the damage indices from visual inspection. The following terminology is used to demote samples: 1W-B-1 denotes first wing box (1 minute exposure), B refers to bottom side of wing (directly exposed to fire) and 1 refers to sample number.

Several trends are clear from the Table. Increased exposure (geometry and time) causes significantly more damage in the composite material. A realistic fire results in non-uniform damage due to non-uniform thermal exposure and must be taken into account during damage assessment. Geometry and thickness variations also affect damage levels.

Photographs of some of the samples are shown below. One minute exposure samples show varying degrees of damage ranging from surface discoloration to scorching and pitting. This may be due to the coating on the composite material (paint or others) burning away. All the 5 minute exposure samples (top and bottom of wing box) show significantly more damage than the 1 minute samples, as expected. In most cases, the 5 minute samples were essentially completely

damaged to the point where property measurements would be impossible. These samples showed very visible resin loss, fiber damage and layer separation (Figures 3 and 4). We can also expect some fiber oxidation and burn damage due to the temperatures measured during the 5 minute burn test.

Table 2: Visual Damage Levels for the Wing Box Samples

Sample Number	Exposure Time	Thickness (mm)	Mass (g)	Visual Damage *
1W-B-1	1 Minute	5.8	294.0	B - 2
1W-B-2	1 Minute	6.1	340.1	A - 3
1W-B-3	1 Minute	8.0	593.3	C - 3
1W-B-4	1 Minute	8.6	713.7	C - 3
1W-B-5	1 Minute	1.9	71.9	C - 2 - LS
1W-B-6	1 Minute	11.1	850.0	C - 3
1W-T-1	1 Minute	8.2	469.8	A - 2
1W-T-2	1 Minute	7.9	499.6	A - 2
1W-T-3	1 Minute	12.6	846.2	A - 1
1W-T-4	1 Minute	4.5	262.5	B - 1
1W-T-5	1 Minute	1.4	85.6	A - 2
1W-T-6	1 Minute	13.2	843.5	A - 1
2W-B-1	5 Minute	7.5	229.6	D - 2
2W-B-2	5 Minute	N/A	160.7	D - 3
2W-B-3	5 Minute	11.4	495.2	D - 2
2W-B-4	5 Minute	4.6	67.2	D - 3
2W-B-5	5 Minute	N/A	148.2	D - 3
2W-B-6	5 Minute	18.9	465.7	D - 2
2W-Debris	5 Minute	N/A	406.8	B - 3
2W-T-1	5 Minute	N/A	338.8	D - 1
2W-T-2	5 Minute	N/A	91.5	D - 3
2W-T-3	5 Minute	20.8	1057.1	D - 1
2W-T-4	5 Minute	6.2	94.6	D - 3
2W-T-5	5 Minute	2.4	28.2	D - 3
2W-T-6	5 Minute	15.9	732.9	D - 1

Typical thermal profiles are shown in Figure 5 for both burn tests, as measured on the exposed side (bottom) of the wing boxes. As expected, the 5 minute burn results in composite ignition and continued heat release and burn despite extinguishing the flame, indicating deep-seated fires within the structure. Optical micrograph and SEM analyses are ongoing.

Figure 1 Photographs of two samples (1W-T-6, 1W-T-1) from top-side of Wing Box 1 (1 minute exposure)

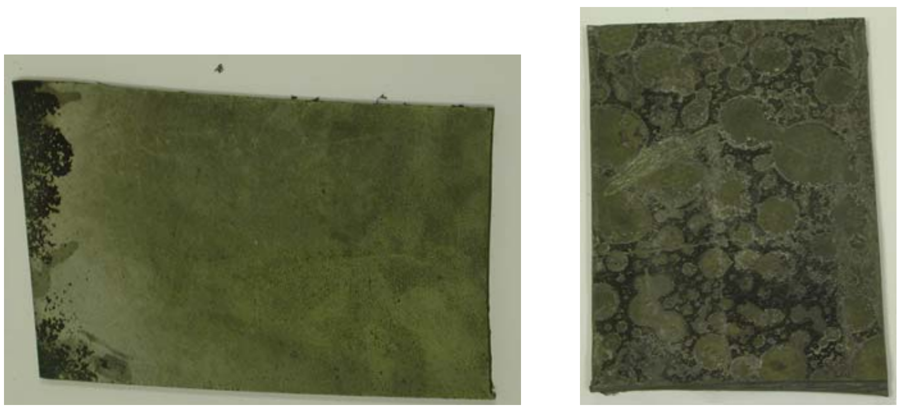

Figure 2 Photographs of two samples (1W-B-1, 1W-B-3) from bottom-side of Wing Box 1 (1 minute exposure)

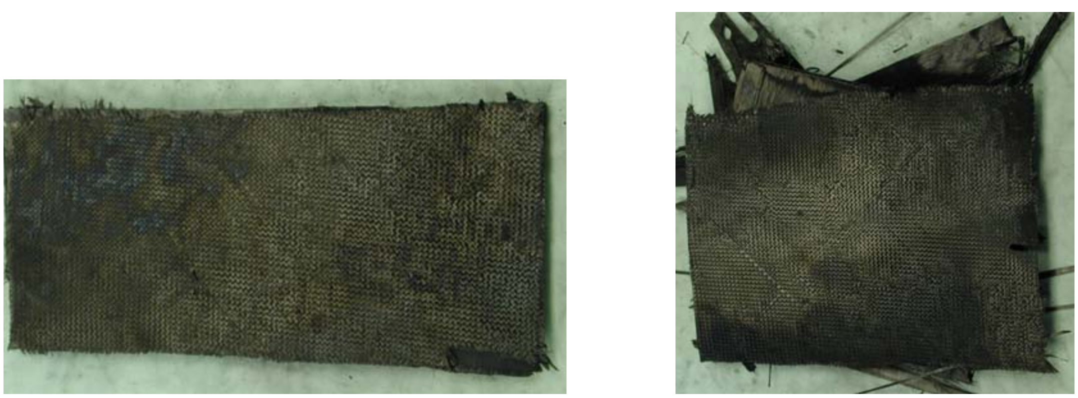

Figure 3 Photographs of two samples (2W-T-6, 2W-T-1) from bottom-side of Wing Box 2 (5 minute exposure)

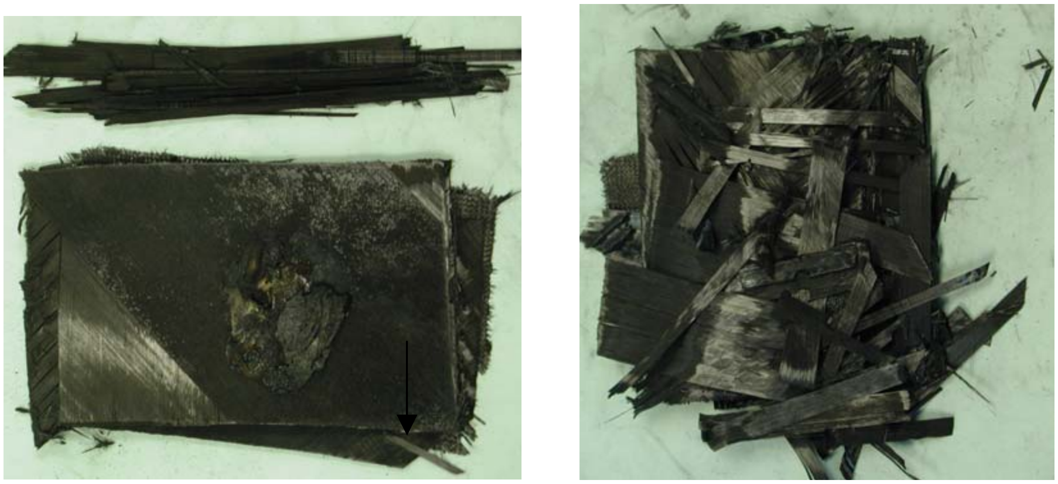

Figure 4 Photographs of two samples (2W-B-1, 2W-B-2) from bottom-side of Wing Box 2 (5 minute exposure)

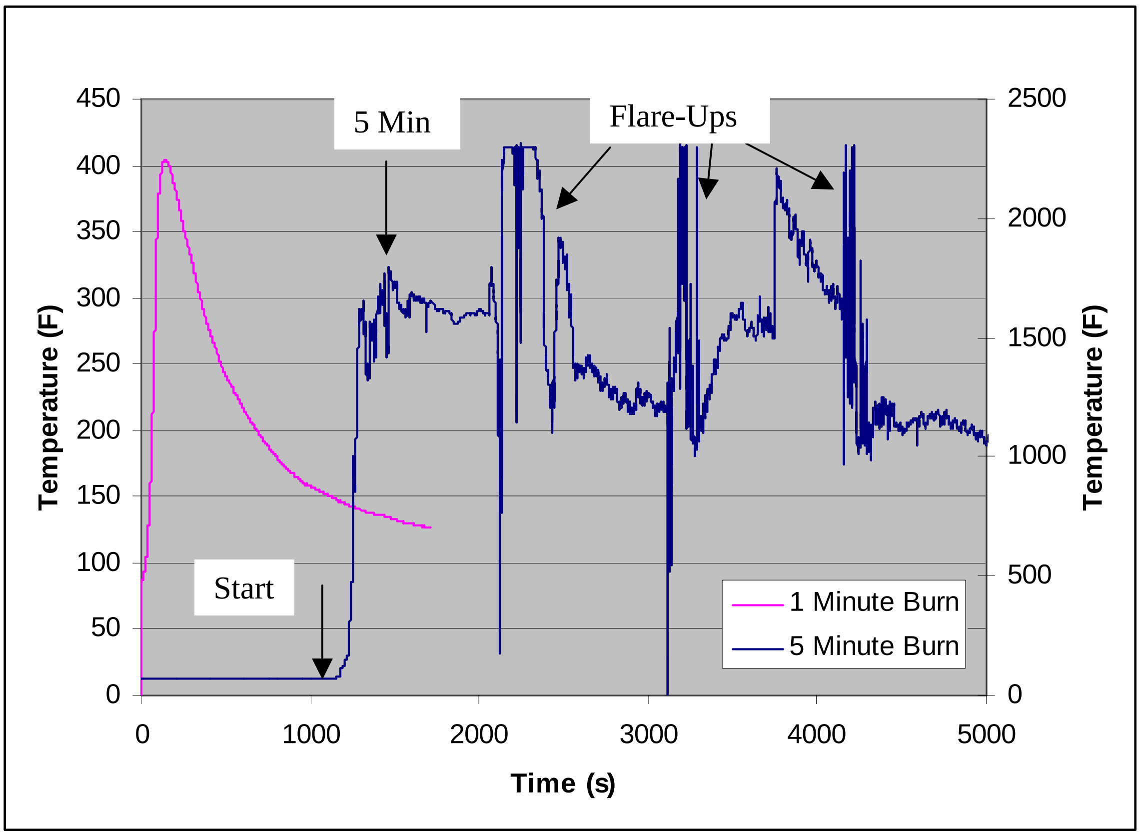

Figure 5 Typical Thermal History of Samples from both Wing Boxes

3.2 DEGRADATION ANALYSIS

Based on the visual examination of the specimens, it was determined that the samples of primary interest are the 1W-B series and any useable samples from the 2W series. Initial evaluations looked at moisture content of as received samples. Specimens from different sections of the

various samples were dried for a period of 3 days at 80 C and weight change measured. Average weight loss was approximately 0.4% for the entire range of specimens tested, which indicates a small uptake of moisture after the burn tests. This is of interest due to the use of water as an extinguishing medium and the corresponding uptake levels in the composite.

Thermogravimetric analysis of wing box samples was done using a TA Instruments Q500 TGA. Air was used as the purge gas with a flow rate of 5C/min. Figure 6 shows the averaged weight loss of the sample as a function of temperature. Initially 0.5% weight loss up to 140C was observed, indicating the moisture lost which agrees well with our drying experiment measurement (~0.4%). The next significant step occurred at 1.2% up to 248C, which maybe due to decomposition of the surface coating (paint etc) of the wing box. However, this needs to be verified with additional experiments. The third weight loss (10%) step occurs up to 382C followed by 40% weight loss up to 630C, which correlates well with the expected resin content (~ 40%). The final weight loss of approximately 92% is due to carbon fiber decomposition. However, depending on the heat flux (much higher in a fire compared to the TGA) and thermal properties of the fiber and resin decomposition may have occurred at lower temperatures in the wing box samples. The TGA results indicate an “idealized” decomposition pattern of the composite material used in the wing box. Further investigation is ongoing.

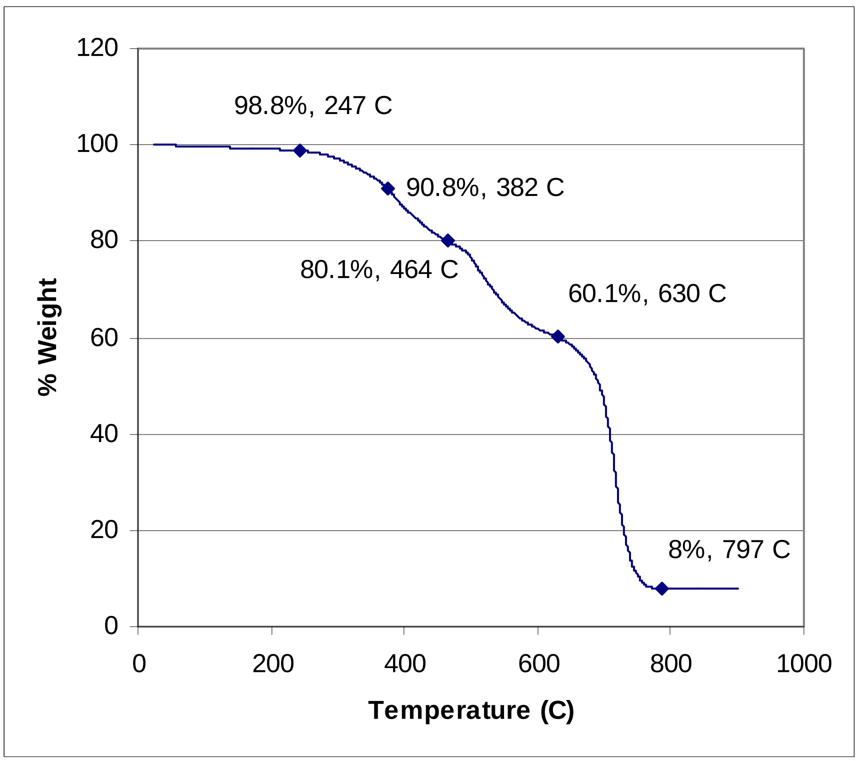

Figure 6 Degradation Behavior of AS4/3501-6. Sample from 1 minute Wing Box (1W-T-4)

3.3 THERMO-MECHANICAL ANALYSIS

Initial analysis focused on density measurements and correlation with the glass transition temperature (Tg). It is well known that changes in Tg can be correlated well with composite degradation mechanisms of cross-linking and chain scission and DMA measurement were done to assess Tg changes in the samples. A TA Instruments DMA 2940 was used for this purpose and

specimens were cut from the wing box samples for a dual cantilever clamp setup. Measured values for both 1W-B and 2W-B samples are shown in Table 3, along with density and short beam shear strength values. Temperature ranges listed are estimates based on thermocouple readings, due to the non-uniformity of the flame source and may be higher than recorded.

Table 3 Thermo-Mechanical Assessment for Fire-Exposed side of Wing Boxes

Sample Number	Typical Temperature Range	Average Density (g/cc)	Average Tg (C)	Average Short Beam Shear (psi)
1W-B-1	Up to 425 F	1.529	192	7802
1W-B-2	Up to 425 F	1.552	173	9376
1W-B-3	Up to 425 F	1.538	170	10900
1W-B-4	Up to 425 F	1.541	170	9869
1W-B-5	Up to 425 F	N/A	210	N/A
1W-B-6	Up to 425 F	1.548	192	9852
2W-B-1	1400-1800 F	Full Degradation	N/A	0
2W-B-2	1400-1800 F	Full Degradation	N/A	0
2W-B-3	1400-1800 F	Full Degradation	N/A	0
2W-B-4	1400-1800 F	Full Degradation	N/A	0
2W-B-5	1400-1800 F	Full Degradation	N/A	0
2W-B-6	1400-1800 F	Full Degradation	N/A	0

Measured densities show significant variation in each individual sample as well as across wing box. This may be due to the non-uniform thermal exposure and associated localized changes in weight loss (loss of coating etc). Tg measurements show similar wide variations with some of the 1W samples (B-1 and B-6) showing increases, which may be due to the post-cure effect. Hercules datasheets show that AS4/3501-6 increases in Tg to 227C when post cured at 350 F (177 C) for 4 hours. Low levels of fire exposure, such as the 1 minute test may cause increased cross-linking and an increase in Tg, but this will also make the resin more brittle due to a decrease in toughness thus affecting composite performance.

A comparison of Tg vs measured density is shown in Figure 7 for the 1 minute and 5 minute samples. The higher exposure samples (that were measurable) show a consistently high Tg compared to the lower exposure samples. While Tg values are reasonably consistent for the 1W samples, the wide variations in density may be due to the following reasons: coating loss on samples showing some surface damage will reduce density (reductions average ~4%), while samples that show scorching and pitting may have localized resin loss, thus artificially increasing

density. All the 2W samples will show lower density due to fiber oxidation and resin decomposition. This hypothesis is being further investigated and validated.

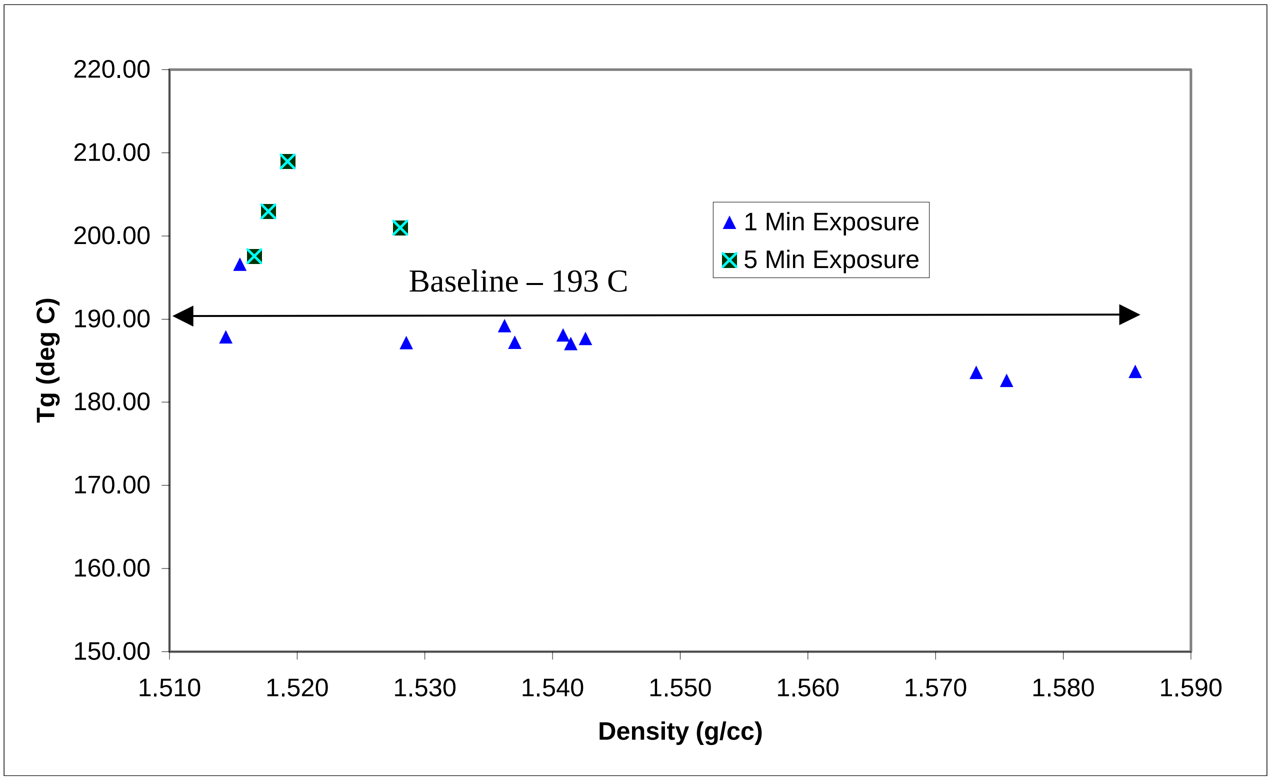

Figure 7 Density and Tg variations in the Wing Box Samples

Short beam shear strengths were measured for specimens from both wing box samples. Average values are listed in Table 3, with the actual values plotted as a function of density in Figure 8. The trend of decreasing shear strength with decreasing density is clear and an examination of the failure modes shows a mix interlaminar shear and tension/compression failure. This is expected due to the surface damage on the 1W samples and ongoing flexure tests are expected to better quantify the effect surface damage.

4. DISCUSSION

The methodology outlined for post-fire damage assessment of the composite wing boxes has identified several key issues. Wing box 1, which simulated a rapid response shows some measurable change in thermo-mechanical performance of the composite material, as quantified by density variations, Tg changes and short beam shear strength variations. Visual inspection confirms significant coating damage in some of the samples exposed directly to the pool fire, and is also corroborated with thermo-mechanical performance. Delayed response allows composite ignition and heat release, which essentially causes the material to burn itself out, thus completely degrading the structure beyond repair.

Based on the property assessments in the wing box samples, fire damage can generally be classified into four zones as shown schematically in Figure 9, irrespective of thermal history.

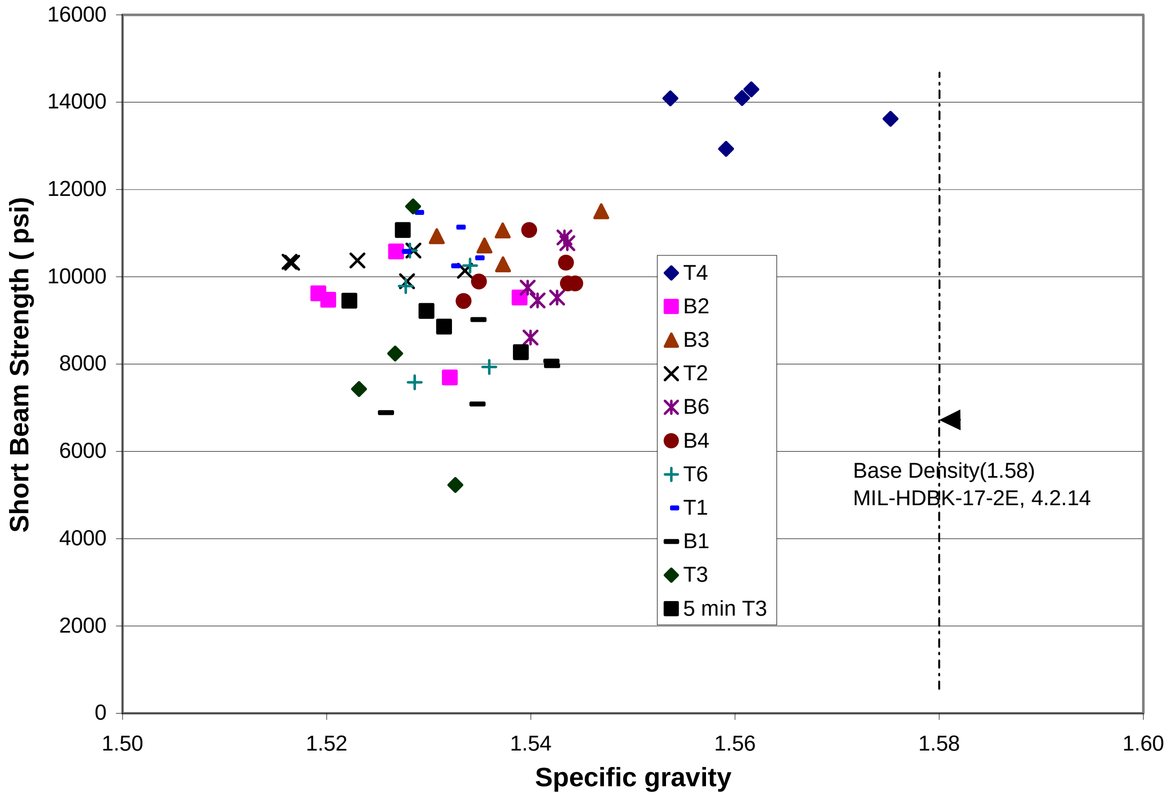

Figure 8 Short Beam Shear Strengths as a function of Wing Box Sample Density

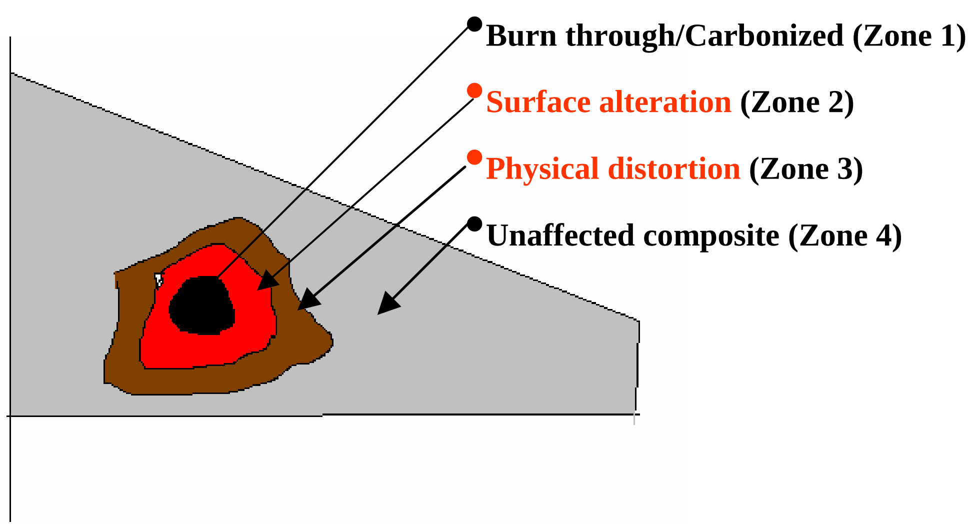

Figure 9: Schematic of typical burn zones due to fire damage

- Zone 1-Complete carbonization/burn through

  Wing box 2 (entire 2W-B series samples and most 2W-T)

  Maximum damage occurs at the area exposed to the highest thermal exposure (Zone 1) and can be severe – burn through and carbonization of the fibers. This zone will also

show the maximum weight loss (up to 100%) depending on the severity of damage. Performance assessment of this zone will be limited to visual inspection, weight loss and density change as any other assessment is essentially meaningless.

- Zone 2- Surface oxidation/chemical alteration

  Wing box 2 (2W-T-3, 2W-T-6)

  This zone will show significant alteration in chemical structure of the material due to degradation kinetics. Weight loss in this zone may be significant and can contribute to large-scale property degradation. Damage assessment in this zone will involve visual, weight loss and density measurements, followed by thermo-mechanical property evaluation to understand degradation kinetics of the material.

  Surface characterization of the damaged material from zone 2 is important to understand the material and fiber/matrix interface degradation to correlate with the exposure time and temperature.

- Zone 3- Mechanical distortion due to heat

  Most of Wing box 1 (1W-B samples and some 1W-T)

  This zone may have some visual damage due to exposure of heat (especially paint, coatings etc) and mechanical distortion of the composite may occur that ultimately changes the performance. Parameters that will be used for damage appraisal of this zone include Tg change, Density /Volume change, Surface characterization and NDE for internal damage.

  This is a critical zone as it delineates unrepairable material from that which can be repaired to restore mechanical performance.

- Zone 4- Undamaged material

  Some of Wing box 1 (some 1W-T samples)

  This zone represents material that has not seen degradation level temperatures (thermal history stays below at or below Tg), though some post-curing effect may be evident depending on the resin system. Thermo-mechanical properties are not expected to vary significantly from the baseline composite material.

This description is independent of the thermal history, as change in exposure will either reduce or eliminate zones, and the description is more a function of the degradation characteristics of the composite material. The proposed damage classification is a first generation description and methodology for post-fire damage assessment of composite materials and can be applied to a variety of applications.

5. CONCLUSIONS

A post-fire damage assessment was conducted for composite wing boxes that had been exposed to simulated pool fire tests. Two scenarios were tested: the first simulated an immediate response to a pool fire by a person located near the aircraft utilizing the standard 150 lb. Halon 1211 fire extinguisher and the second fire simulated a handline from a P-19 response containing 3% AFFF

solution, five minutes after fire ignition. The damage assessment methodology focused on visual examination, composite degradation kinetics, changes in density, Tg and short beam shear strength properties for samples from the top and bottom sections of both wing boxes. A common feature in all samples was the non-uniformity in damage levels, both from visual examination and measured properties, reflecting variations of thermal history in realistic fire exposures. In addition, damage assessment in a real fire will generally be with an unknown thermal history. Based on the assessment of the wing box samples, a damage-zone based description and methodology has been outlined that can be applied to composite materials in a variety of applications.

6. ACKNOWLEDGMENTS

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